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To: Dr. D. Mills
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THE FORWARD SCATTERING SPECTROMETER PROBE

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A Particle Measuring Systems (PMS), Forward Scattering Spectrometer Probe (FSSP), Model FSSP-100 has been acquired by the Environmental Science Section (ESS). The FSSP uses laser-light scattering to size airborne particles between 1 and 95 μm in diameter. The FSSP is an extremely robust instrument that has been applied by the ESS to size water droplets in steam at 100°C and in natural fogs at above- and below-freezing temperatures. This report describes the operating principles of the FSSP, describes modifications made to the operating software and documents operating procedures.

1.0 INTRODUCTION

The Particle Measuring Systems (PMS), Forward Scattering Spectrometer Probe (FSSP), Model FSSP-100, is a device that uses laser-light scattering to size airborne particles between 1 and 95 μm in diameter. The FSSP is an extremely robust instrument, designed for aircraft and ground-based use under a variety of environmental conditions. The FSSP may also be readily adapted for use in the laboratory. The instrument has found application in measuring drop size distributions of naturally occurring fogs and clouds, in wind tunnel studies of droplet dispersion and in nozzle spray characterization.

The Environmental Science Section purchased an FSSP as part of a CANDU Owner's Group (COG) funded program to study water aerosol formation and behaviour following a Loss of Coolant Accident (LOCA). These studies necessitated the measurement of water droplet size distributions in a steam atmosphere at 100°C. Non-intrusive techniques, such as light scattering, seemed to provide an ideal means of making these measurements. A program to adapt the FSSP to these conditions was therefore embarked upon, recognizing that the ability to sample aerosols in harsh environments would be a capability useful in other applications.

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This report describes the operating principles of the FSSP, describes modifications made to the operating software and documents operating procedures. Software was also established to derive means, moments and cumulative distributions from the raw size distributions (particle concentration versus size).

2.0 THE FSSP

2.1 Principle of Operation

The optics of the FSSP are shown schematically in Figure 1. A 5-mW, 632.8-nm wavelength hybrid He-Ne laser beam is focused to the sampling point in the air flow. Particles carried in the air stream past the sampling point scatter light out of the beam. The intensity and spatial distribution of the scattered light depends on the particle diameter (as well as the refractive index of the particle and the wavelength of the laser beam). The FSSP analyzes the light scattered in the forward direction into a hollow cone surrounding the beam axis (typically between about 4° and 14° of the beam axis) to derive particle sizing information.

The beam width at the point of focus is about 0.2-mm diameter with about 2.5 mm of beam length contributing to detected signals (this length is termed the instrument depth-of-field, DOF). The instrument therefore samples a cross-section of about 0.5 mm^2 of the gas flow.

After passing through the sampling region, the main laser beam is intercepted on an opaque dump spot (1-mm diameter) on the face of a right-angle prism. The forward scattered light passes through the prism and is re-focused by the collecting lens and centred onto a 50% beam splitter. Half the light illuminates a photodetector (the ***signal*** detector) and the other half illuminates a photo-detector partially masked by a second circular dumpspot (the ***annulus*** detector). The ***annulus*** detector thus only responds to light scattered through larger angles whereas the ***signal*** detector responds to total forward scattered light.

Particles passing through the beam relatively far from the focus scatter proportionally more light into the ***annulus***. Comparison of the ***signal*** and the ***annulus*** outputs thus allows the depth-of-field, (ie, the sampling region) to be accurately defined.

The ***annulus*** and ***signal*** detector outputs are amplified, conditioned and processed by the FSSP electronics. The ***signal*** voltage is converted to particle size using a 15-channel pulse height analyzer whose comparison levels are preset to certain size levels. The probe sizes particles in four size ranges (5 to 95 µm, 2 to 47 µm, 2 to 32 µm, and 1 to 16 µm) with each range divided into 15 equally spaced bins.

To discriminate against particles that pass close to the beam edge and may be undersized, a running average of particle transit times is electronically maintained (for those particles that pass through the DOF). Particles with transit times shorter than the average are rejected (on the assumption that they have passed through a shorter chord on the outer edges of the beam) and particles with greater transit times than the DOF average are accepted.

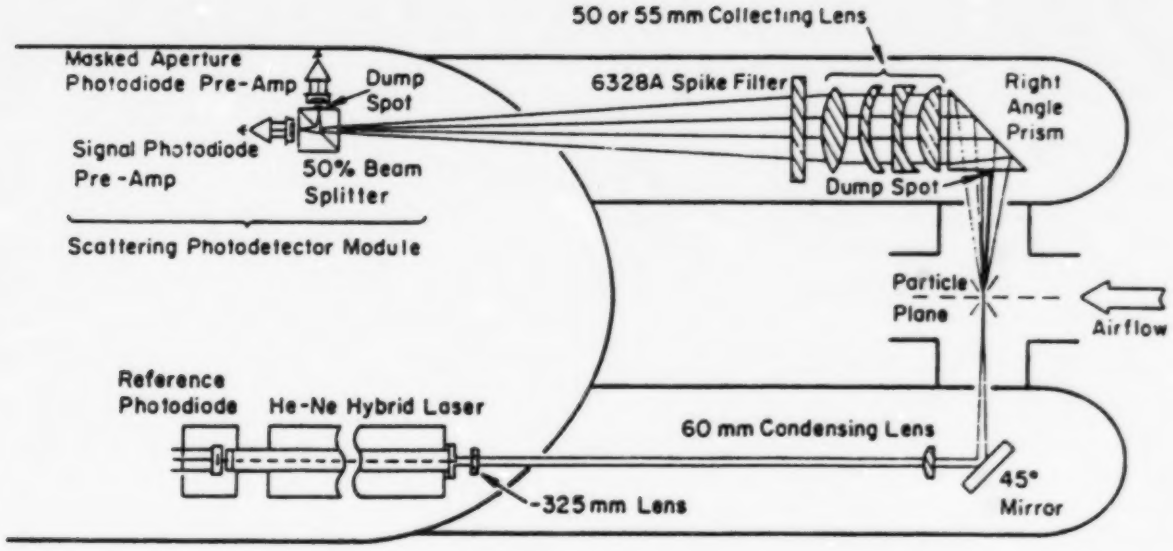


FIGURE 1

A SCHEMATIC SHOWING THE OPTICAL PATH AND COMPONENTS IN THE FSSP

After the particle exits the beam, a delay period occurs during which the particle sizing information is recorded. The delay time is about 10.5 μs for particles passing through the DOF and about 2.5 μs for particles that give rise to detectable signals but pass through the beam outside the DOF. These are referred to as the ***slow delay*** and ***fast delay*** times, respectively. During these periods the probe is insensitive to other particles that enter the beam resulting in undercounting. To correct for this, the probe records the accumulated time the electronics are active (activity) and a correction algorithm may be applied (Appendix B).

Figure 2 gives a schematic flowchart of the response of the FSSP to the signal from a particle passing through the beam.

To size particles correctly, the air velocity through the sampling region should be greater than 10 m s^{-1}. When making measurements in still or slowly moving air, the probe can be fitted with an aspirator horn (of exponential profile) and fan to draw the sample through the laser sampling point at high enough velocity (>20 m s^{-1}).

A detailed description of the FSSP and its operating principles may be found in the cited references by Baumgardner et al and others.

2.2 FSSP Electronics

The FSSP electronics are divided into six stages as shown in Figure 3. These stages have the following functions:

(1) amplifies photodetection (***signal*** and ***annulus***) voltage;

(2) provides baseline restoration after amplification of the ***signal*** and ***annulus*** voltages;

(3) compares the ***annulus*** and ***signal*** voltages and determines whether a particle has passed through DOF;

(4) classifies the ***signal*** voltage into one of 15 class sizes (pulse height analyzer, PHA);

(5) maintains a counter proportional to a moving average of the transit times of all particles passing through the DOF that are of acceptable size limits and compares particle transit time to this average to determine whether pulse should be registered; and

(6) provides the timing signals for the remainder of signal processing for accepted particles and generates a reset pulse which readies the FSSP for the next particle.

2.3 FSSP Control and Data-Processing Hardware and Software

Control and Data-Logging

The FSSP operating mode and data acquisition and display are controlled by the PMS Model 1058 1-D probe adaptor module which is a printed circuit designed to occupy any slot in an IBM PC/AT or compatible computer. An Enhanced Graphics Adaptor with colour CRT monitor is also required. The adaptor module interfaces the probe directly to the computer system via a single 5-m interconnecting cable. The probe signal cable was extended to 23 m to allow flexibility and

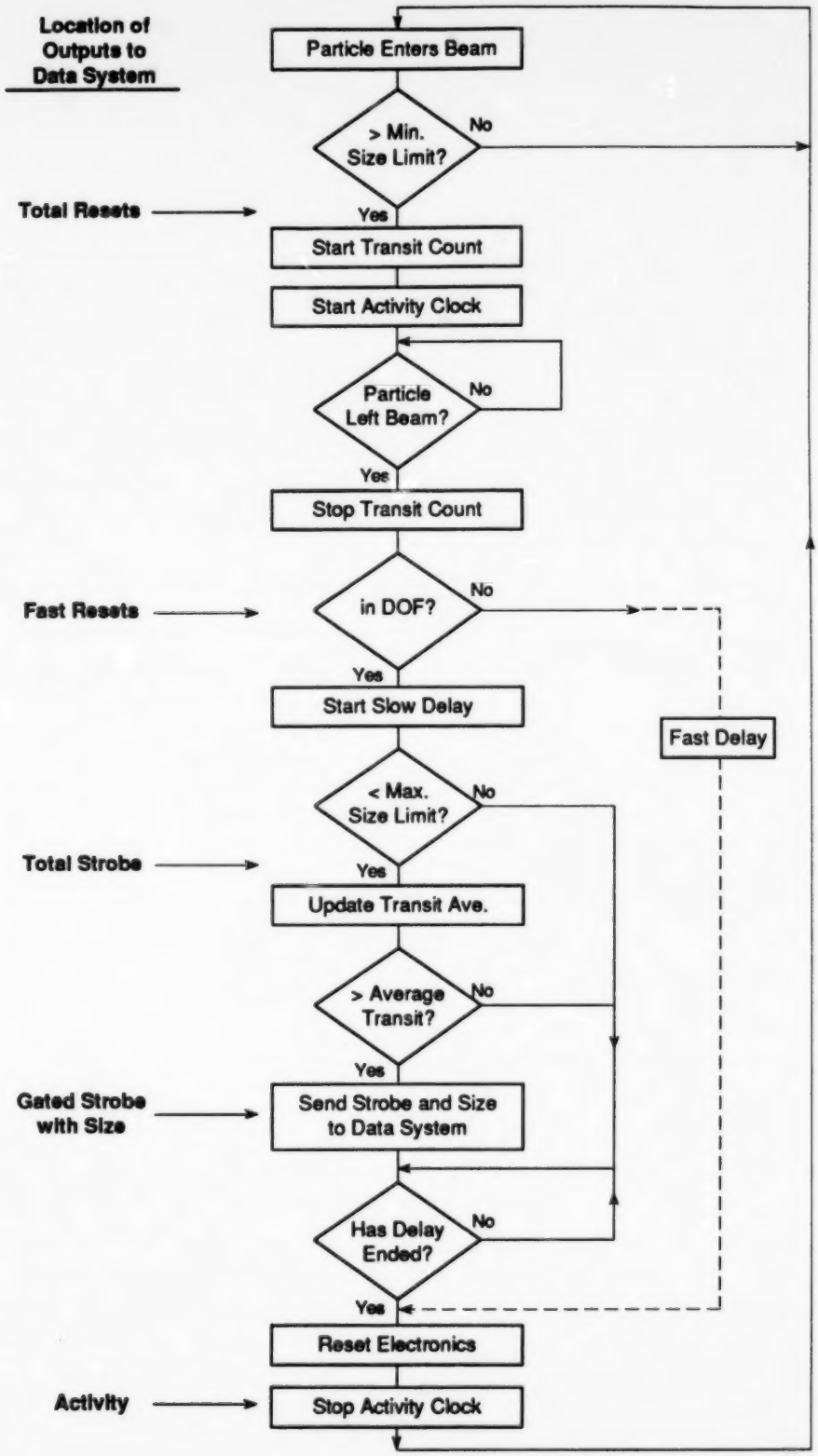


FIGURE 2

A FLOWCHART SHOWING THE SEQUENCE OF EVENTS AS A PARTICLE IS DETECTED BY THE FSSP. THE DASHED LINES SHOW THE ADDITIONAL LOGIC FLOW FOR PROBES WITH FAST RESETS. (AFTER DYE AND BAUMGARDNER, 1984)

181799-B14-RD

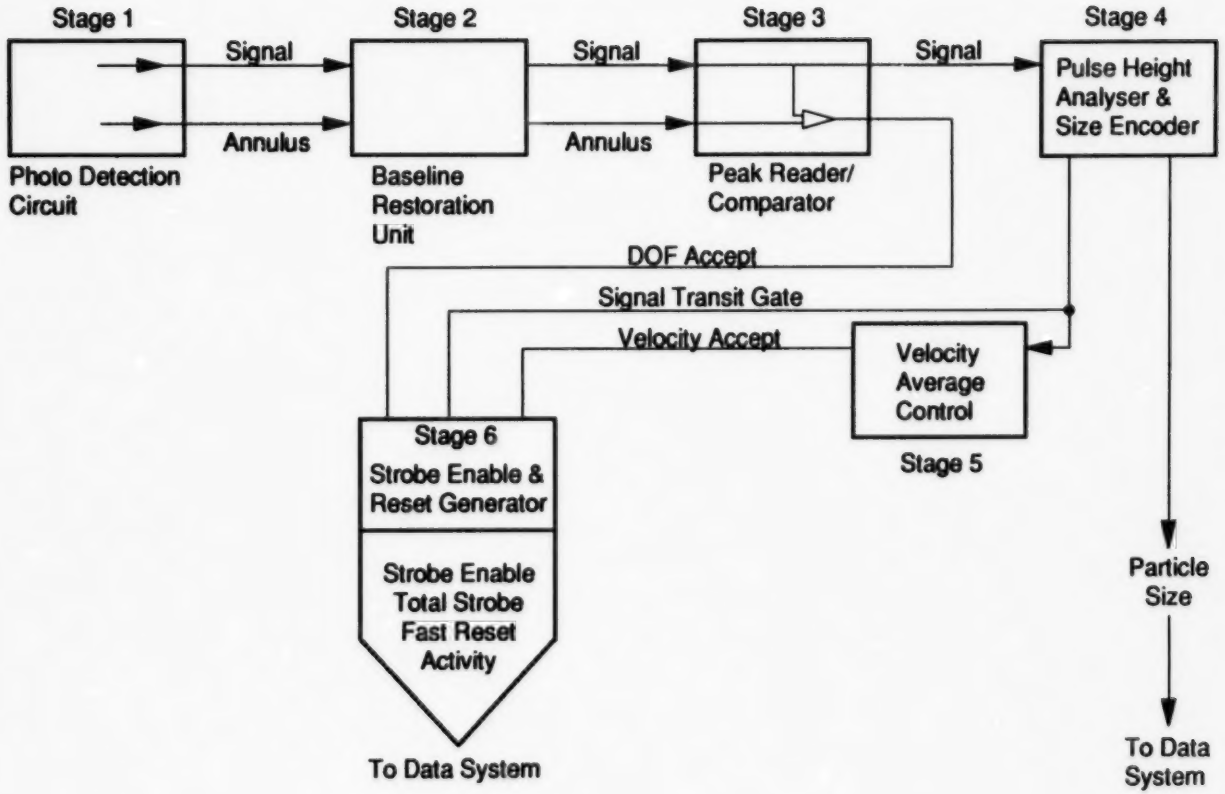


FIGURE 3

ILLUSTRATION OF BASIC STRUCTURE & FUNCTION OF FSSP CIRCUIT (AFTER DYE AND BAUMGARDNER, 1984)

89-297 179919-C8-RD

to isolate the computer system from the harsh environment to which the probe is occasionally subjected.

The adaptor module package includes diagnostic software which checks all the features of the module for proper operation.

As supplied by the manufacturer, the FSSP software allows menu-driven computer control of the system operating parameters including probe size range, sample averaging time and sample display in histogram form on the CRT monitor. As supplied by PMS, the software did not have a facility to store data files and histogram values had to be manually recorded.

To overcome this difficulty and allow data to be stored directly on computer files, the software was modified by Research Division. The operation of the modified software is as follows:

(1) First, executing program 1D results in the CRT display as shown in Figure 4. Default values can be changed by using the cursor keys to highlight the appropriate field (PROBE, READ SEC, ACCUM SEC, CURRENT SEC) and then entering a desired value or using the "+" key to select options, as appropriate. The auxiliary channel fields located at the bottom right of the screen also require "+" key response to enable/disable each field. A description of the user input fields and their input ranges is also given in Figure 4. The main display shows a histogram of accumulated particle counts in each size range; the histogram is updated in real time.

(2) After sampling parameters have been set, sampling is initiated by typing "C" which instructs the logging program to open a data file. The following three responses are prompted.

>"Write collected data to file"- (Y/N)? Y (<---)
- ENTER FILENAME WITHOUT EXTENSION (8 CHARS MAX) (<---)
- ENTER ONE LINE DESCRIPTIVE COMMENT (<---)

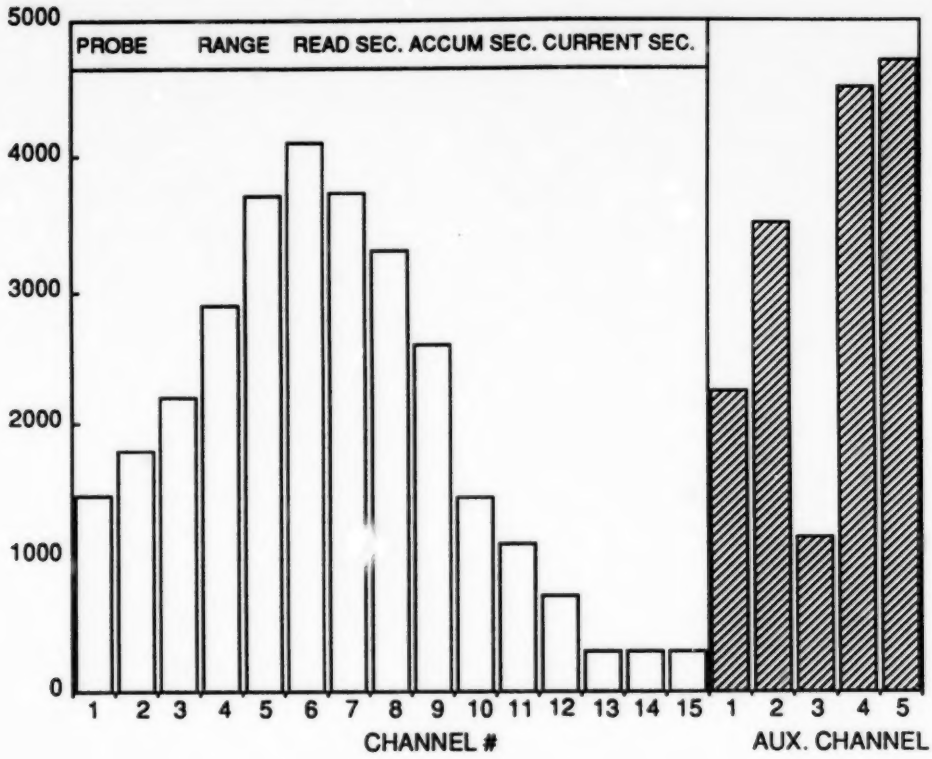
Files are stored as filename.EXT where EXT is automatically incremented by 1 for each file generated. Files will only be saved after accumulation seconds equals current seconds. To use the data analysis program listed below, the filename should be entered in the comment line.

Pressing the space bar freezes the current display. Re-pressing the space bar resumes display updating. The "ESC" key terminates and exits the program.

Data Analysis

A LOTUS 1-2-3 program, FSSP.WK1, was written to process ASCII files created by the FSSP data logging program. A listing and detailed description of the program is given in Appendix A. Within FSSP.WK1, three macros have been set up to further reduce operator intervention.

Once the key file FSSP.WK1 has been retrieved, typing "Alt R" prompts the user to enter the logged ASCII filename after which the program imports and processes the selected data file. Some information is not recorded automatically with the FSSP ASCII data file and must be input manually. Table 1 lists the manual edits required to define specific operating parameters.



Fields	Selectable
Probe (1 - 4) - capable of monitoring up to 4 probes.	"+" key
Range (0 - 3) - size ranges where range 0 = 5 - 95 µM 1 = 2 - 47 µM 2 = 2 - 32 µM 3 = 1 - 16 µM	"+" key
Read Sec (0 - 9999) - Sample Frequency	Numeric Input
Accum Sec (0 - 9999) - Accumulation	Numeric Input
Current Sec - Current portion of selected accumulation time (when current sec equals accum sec file is stored with pre-selected file name)	
Channel # For single probe set to 1 - 15	"+" key
Aux Channel - Channel # 1 to 3 are disabled, channel #4 activity output, channel #5 total strobes	"+" key

FIGURE 4

CRT DISPLAY FROM FSSP CONTROL/DATA AQUISITION SOFTWARE

TABLE 1

MANUAL ENTRIES FOR DATA ANALYSIS PROGRAM FSSP.WK1

Line 46	Sampling Velocity
47	Particle Density
48	Beam Width
49	Depth of Field
50	Slow Reset Time
51	Fast Reset Time
52	Activity Correction Factor
70	Test
72	Sample Location
73	Sample Tube Length
74	Sample Tube Diameter

Once editing is complete, invoking the macro "Alt P" outputs a table summarizing the processed data as shown in the example of Figure 5.

As can be seen from Figure 5, the program FSSP.WK1 calculates the following:

- cumulative volume distribution (plot optional);
- volume mean droplet diameter and standard deviation;
- geometric mean droplet diameter and geometric standard deviation;
- cloud liquid water content (uncorrected for sampling efficiency);
- cloud liquid water content (corrected for sampling efficiency); and
- total droplet counts.

3.0 FSSP CALIBRATION AND CHARACTERIZATION

The calibration procedures documented below should be carried out regularly to determine and/or verify the operating characteristics of the probe. These tests are termed ***static*** and ***dynamic***. The static calibration involves measuring and verifying laser output, depth of field, beam diameter, sample velocity, sample volume and checking the zero count. The dynamic calibration checks the accuracy of FSSP size-range measurements using calibration beads. Calibration methods and results are described briefly below.

3.1 Static Calibration

1) **Laser Output** - The reference voltage meter supplied by PMS is connected to the probe to monitor laser output. When the reference voltage decreases to about 7.0 V the laser tube should be replaced. The Research Division probe currently measures 8.5 V which is acceptable.

2) **Depth of Field (DOF)** - The DOF of the laser beam was determined by traversing a 30-μm diameter Nylon fibre across the beam path. The fibre was held by a micropositioner which moves in the x-y axis. When the fibre is centred in the beam, the ***signal*** voltage output is maximum. By traversing the fibre along the beam path the limits of the DOF can be determined as those points at which the ***signal*** voltage equals the ***annulus*** voltage (Baumgardner et al 1984). The DOF measured in this way was 2.4 mm.

FIGURE 5

EXAMPLE OF DATA OUTPUT FROM FSSP AFTER PROCESSING

File:
Test:
Date: 15:11:88 Time: 16:55: 5
Sampling Location:
Sampling Tube - Length (cm):
- Diam (cm) :

Channel No.	Diam (um)	Counts	Percent Counts	Volume Percent	Cumulative Percent Volume
1	2	185018	46.2	1.9	1.9
2	3	90845	22.7	4.3	6.2
3	4	50760	12.7	6.6	12.8
4	5	28090	7.0	7.8	20.6
5	6	15329	3.8	7.7	28.3
6	7	9786	2.4	8.2	36.5
7	8	6511	1.6	8.3	44.8
8	9	4575	1.1	8.5	53.4
9	10	3265	0.8	8.5	61.9
10	11	2220	0.6	7.8	69.7
11	12	1554	0.4	7.2	76.9
12	13	1081	0.3	6.4	83.3
13	14	743	0.2	5.6	88.8
14	15	570	0.1	5.3	94.1
15	16	520	0.1	5.9	100.0

Geometric mean diameter (um) 2.4 Geometric S.D. 1.7
Volume mean diameter (um) 8.7 S.D. (um) 1.3
Cloud density (g/m^3) 0.019 - Uncorrected for coincidence/ dead-time loss
Cloud density (g/m^3) 0.024 - Corrected for coincidence/ dead-time loss (Baumgardner et al)
Cloud density (g/m^3) - Corrected for coincidence/ dead-time loss (probe activity)
Total counts= 4.01E+05

3) **Beam Diameter** - The beam diameter was measured by traversing the fibre across the beam path with the micropositioner. The measured beam path diameter was 0.227 mm.

4) **Aspirator Sampling Velocity** - The sampling velocity (velocity of the air stream at the laser interrogation point) was determined by measuring the volume of air passing through the FSSP during a known time period. A large air bag (100 L capacity) was used for this purpose. The sampling velocity with aspirator fan was 26 m s^{-1}.

5) **Sample Volume** - The effective sample volume is the product of the sampling velocity, DOF and beam width.

6) **Zero Count Check** - This procedure involves blocking the beam path which should eliminate all activity counts. If counts are registered in any of the four ranges, the optics should be cleaned.

3.2 Dynamic Calibration

Dynamic calibration of the FSSP particle size measurement is carried out by flowing monodisperse glass beads of precisely known diameter with an air stream through the laser interrogation point and checking the voltage output against a chart provided by the manufacturer. To achieve the necessary sampling speeds (> 10 m s^{-1}) the inlet and exit of the sampling head (2.5 cm ID) are plugged with stoppers containing 7 mm ID tubes aligned with the laser sampling point. Suction is applied to the exit tube and small glass beads are fed into the airstream entering the entrance tube. During this process the probe should be positioned vertically since beads > 40 µm tend to settle out or travel along the bottom of the tube wall.

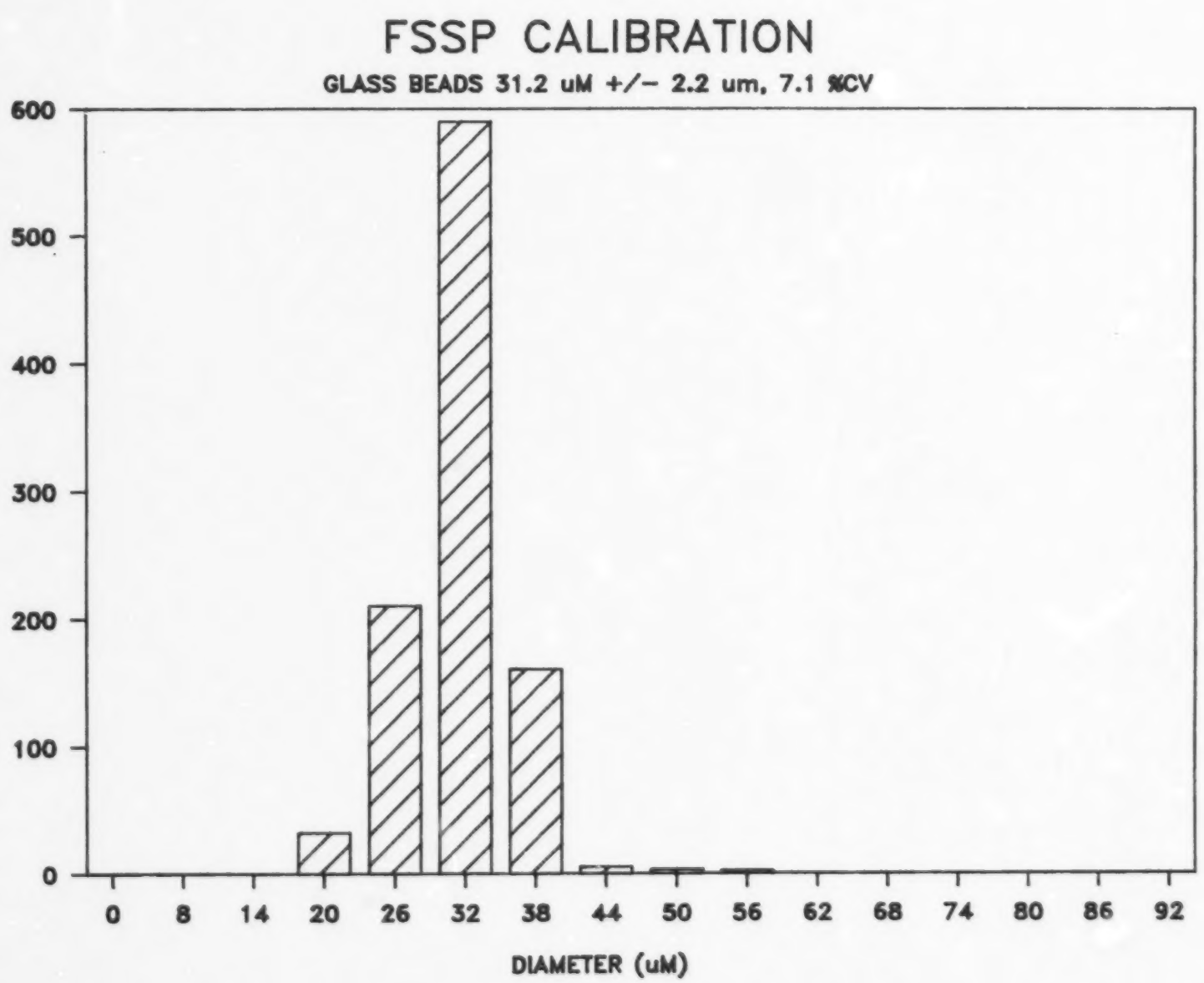
Glass beads should be injected into the sampling flow slowly enough (about 1 mg of beads over a 5-s period) to avoid clumping which will result in an over-estimate of calibration size. If the bead injection rate is too slow, background atmospheric aerosols can bias calibration. If the probe undersizes calibration particles, the optics should be checked for cleanliness and alignment before making electronic adjustments. Figure 6 shows the probe response to injection of 31.2 µm-diameter glass beads. The broadening observed is normal and is due to the slight variations of laser beam intensity within the sampling volume. The peak intensity of the scattered signal thus depends slightly on the particle path through the laser beam. This causes artificial broadening of particle spectra (Baumgardner 1983).

3.3 Electronic Calibration

Atmospheric Environment Service (AES) have designed and constructed an LED calibration unit to check the FSSP electronic system. Research Division have obtained the schematics and are presently constructing a similar unit.

This system tests the FSSP and helps locate faults by electronically generating pulses of known frequency to simulate the light scattered from a particle (or series of particles). These signals can be applied to either the ***signal*** or ***annulus*** circuit, via an LED or connector output. The calibrator can test all four ranges through channels 1-15.

FIGURE 6


FSSP CALIBRATION
GLASS BEADS 31.2 uM +/- 2.2 um, 7.1 %CV
COUNT
600
500
400
300
200
100
0
0
8
14
20
26
32
38
44
50
56
62
68
74
80
86
92
DIAMETER (uM)

The AES calibrator was borrowed to check the Research Division FSSP. The system processing delay time was measured by injecting a pulse to the ***signal*** detector and measuring the time from the rise of the input pulse to the rise of the reset pulse marking the end of processing. This corresponds to the ***slow delay*** for processing signals from particles that pass through the DOF and was found to be 10.5 μs. The ***short delay*** for processing particles that give rise to detectable signals, but do not pass within the DOF, was found to be 2.4 μs.

For tests requiring a measure of response time, a signal was injected through a 100-kΩ resistor at the output of the photodetectors, whereas, for measuring the thresholds of the PHA size channels, the signal was connected directly into the baseline restoration unit (first stage disconnected).

The PHA sizings were checked by injecting pulses of various known amplitudes, and measuring the sizes encoded over a range of the pulse amplitudes. The result fell within prescribed tolerances.

4.0 OPERATING EXPERIENCE

In this section we briefly bring to the reader's attention some aspects of FSSP behaviour that have been established in various studies.

1. Accurate sizing by the FSSP requires a sample flow speed between about 10 m s^{-1} and 100 m s^{-1} (Cerni 1983).

2. The scattering intensity does not always increase monotonically with particle size (particularly in the region below about 10-μm diameter). This can lead to ambiguity in the definition of droplet size and the appearance of artificial peaks in the droplet size spectrum (Pinnick et al 1981, Cerni 1983, Tsonis et al 1987).

3. The FSSP artificially broadens a drop size spectrum which can lead to overestimation of cloud liquid water contents by 10-20%. The sizing resolution is about 10% (Baumgardner 1983, Cerni 1983).

Experience has also shown that probe optics should be routinely checked and cleaned. The optical parameters (DOF, beam width etc) should also be checked after intensive use or probe cleaning and realignment. In our experience, calibration has been reasonably stable over long operating periods (months) requiring little or no maintenance providing condensation of moisture on the optics is avoided.

Our experience with the FSSP in sampling steam environments has indicated that the probe head needs to be water cooled and that steps need to be taken to prevent condensation of steam on the optics. To avoid condensation, a sheath air flow was established around the steam sample flow and the probe was modified to allow clean, dry air flow through the probe casing at about 3 L min^{-1} at moderate overpressure (10 psig).

5.0 CONCLUDING REMARKS

A Particle Measuring Systems, Forward Scattering Spectrometer Probe, Model FSSP-100 has been acquired by the Environmental Science Section. The FSSP uses laser-light scattering to size airborne particles between 1 and 95 μm in diameter. The FSSP is an extremely robust instrument that has been applied by the Environmental Science Section to size water droplets in steam at 100°C and in natural fogs at above- and below-freezing temperatures.

This report described the FSSP, operating procedures, modifications made by Research Division to the data analysis and control software, and information gained to date by Research Division and others on the characteristics of the FSSP. Software was also established to derive means, moments and cumulative distributions from the raw size distributions (particle concentration vs size).

ACKNOWLEDGEMENTS

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APPENDIX A

FSSP Data Analysis Program FSSP.WK1

As discussed in Section 2.3, this program imports raw data files created in ASCII format by the modified FSSP software and calculates

- cumulative size distribution (with optional plot),
- geometric mean diameter and standard deviation, and
- volume mean diameter and standard deviation.

If suitable additional input is provided, the program also corrects for coincidence and dead time losses (Appendix B) and calculates the volume of sampled air and the cloud density (liquid water content for water aerosol).

The program is written as a LOTUS 1-2-3 spreadsheet. Table A1 shows a printout of the spreadsheet display which is organized in four sections: (1) the raw input data, (2) probe operating parameters (input and derived), (3) an output table giving processed data, and (4) program macros.

TABLE A1

FSSP DATA ANALYSIS PROGRAM FSSP.WK1

```
            Lotus File: FSSP            22 Nov 1988
-------------------------------------------------------------------------------
Processes ASCII Files Created by PMS-FSSP Data Logging System
TO RUN: Enter Alt R Followed by File Name When Prompted
TO SAVE FILES: Enter Alt s
TO PRINT: Enter Alt P
-------------------------------------------------------------------------------

1. Raw Data From FSSP File
------------------------------

File =                                          Rep:
Date =                                  15:11:88
Time                                    16:55: 5
Probe number:                                1
Range number =                               3
Reading time (s) =                           1
Accumulation time (s) =                    120
Aux. channel 1 =                             0
Aux. channel 2 =                             0
Aux. channel 3 =                             0
Aux. channel 4 (activity counts)=
Aux. channel 5 (total strobes)=          64998 !x 10 to get total strobes
Channel number =                            16
Channel  0 (counts) =                        0
Channel  1 (counts) =                   185018
Channel  2 (counts) =                    90845
Channel  3 (counts) =                    50760
Channel  4 (counts) =                    28090
Channel  5 (counts) =                    15329
Channel  6 (counts) =                     9786
Channel  7 (counts) =                     6511
Channel  8 (counts) =                     4575
Channel  9 (counts) =                     3265
Channel 10 (counts) =                     2220
Channel 11 (counts) =                     1554
Channel 12 (counts) =                     1081
Channel 13 (counts) =                      743
Channel 14 (counts) =                      570
Channel 15 (counts) =                      520

2. FSSP Operating Parameters (Input and Derived)
-------------------------------------------------
INPUT
Sampling velocity (m/s)                     22
Particle density (kg/m^3)                 1000
Beam width (m)                        2.27E-04
Depth of Field (m)                    2.40E-03
Slow reset time, TAU2 (s)             1.05E-05
Fast reset time, TAU3 (s)             2.50E-06
Activity correction factor                0.55 !PMS recommends 0.7, other authors 0.55.
DERIVED
Particle transit time, TAU1 (s)       1.03E-05
Cumulative "dead" time (s)            1.18E-01 !(TAU3 < TAU1 < TAU2 only)
Sampling area (m^2)                   5.45E-07
Sampled volume (m^3)                  1.44E-03
Acceptance ratio =                        0.62 !Value about 0.63 using aspirator
Activity (fraction) =                          !Should be below 50 % for accurate cloud density
Count Loss Correction factor (probe activity)
Count Loss Correction factor (Baumgardner et al)      1.23 !9th Iteration
Count Loss Correction factor (Baumgardner et al)      1.23 !10th Iteration
Size interval(um)=                            1
Starting size(um)=                            2
```

TABLE A1 (cont'd)

3. Data Output

File:
Test:
Date: 15:11:88 Time: 16:55: 5
Sampling Location:
Sampling Tube - Length (cm):
- Diam (cm) :

Channel No.	Diam (um)	Counts	Percent Counts	Volume Percent	Cumulative Percent Volume
1	2	185018	46.2	1.9	1.9
2	3	90845	22.7	4.3	6.2
3	4	50760	12.7	6.6	12.8
4	5	28090	7.0	7.8	20.6
5	6	15329	3.8	7.7	28.3
6	7	9786	2.4	8.2	36.5
7	8	6511	1.6	8.3	44.8
8	9	4575	1.1	8.5	53.4
9	10	3265	0.8	8.5	61.9
10	11	2220	0.6	7.8	69.7
11	12	1554	0.4	7.2	76.9
12	13	1081	0.3	6.4	83.3
13	14	743	0.2	5.6	88.8
14	15	570	0.1	5.3	94.1
15	16	520	0.1	5.9	100.0

Geometric mean diameter (um)	2.4	Geometric S.D.	1.7
Volume mean diameter (um)	8.7	S.D. (um)	1.3
Cloud density (g/m^3)	0.019	- Uncorrected for coincidence/ dead-time loss	
Cloud density (g/m^3)	0.024	- Corrected for coincidence/ dead-time loss (Baumgardner et al)	
Cloud density (g/m^3)		- Corrected for coincidence/ dead-time loss (probe activity)	
Total counts=	4.01E+05		

TABLE A1 (cont'd)

```
4.  MACROS
----------

\R                              !Imports and processes file, and
{goto}e12~                      creates graph of cumulative volume
/fit{?}~                        percent vs d.
{goto}e15~
/dpfcie15.e41~
oe16.e41~g
/wdre15~
/ce12~B69~
/ce13~b71~
/ce14~d71~
/ce12~a127~
/gtxxb81.b95~aF81.f95~
ots{esc}
 File name
~
{esc}
v


\S                              ! Saves .wk1 and .pic files
~                               N.B. Default file directory must be set
/ce12~a138~                     before running \S.
/ce12~a141~
/fs
 File name
~
/gs
 File name
~
Q


\P                              ! Prints data table.
/ppra69.g109~
agq
```

APPENDIX B

FSSP Detection Efficiency - Acceptance Ratio and Coincidence and Dead-Time Losses

1. Acceptance Ratio

The FSSP sampling area is defined by the product of the beam width and the depth-of-field (DOF). However, a certain fraction of the particles that pass through the beam sampling area are ***transit time (or velocity) rejected*** in order to discriminate against those particles that pass through the edges of the beam. These particles give rise to scattered light of reduced intensity and would be undersized. The ratio of accepted particles to total particles passing through the DOF is the ***acceptance ratio*** and may be calculated directly from the probe output. The number of velocity accepted counts is simply equal to the total number of counts summed over all size channels. The total number of particles passing through the DOF (during the sampling period) is given by the ***total strobes*** output of the FSSP (Section 2.3). The ***acceptance ratio***, AR, is therefore

$$AR = \frac{\text{Total counts}}{\text{Total strobes}} \qquad \text{(B1)}$$

Note that the output from the probe designated "total strobes" must be multiplied by 10 to give the actual number of total strobes.

2. Coincidence and Dead-Time Losses

For high particle concentrations, it is possible that a second particle will pass through the beam while a previous particle is in the beam or while the signal from a previous particle is being processed. In both cases the second particle may not be detected. These losses are termed ***coincidence*** and ***dead-time*** losses, respectively.

The program FSSP.WK1 corrects for these losses in two ways. The first method relies on the ***activity output*** supplied from the FSSP, which is proportional to the cumulative time during the sampling period when the probe electronics are active monitoring and processing a particle signal (each particle contributes a time increment equal to the sum of the particle transit time and the delay time required to process the particle signal, Section 3.3). The ***activity output*** is a number equal to this cumulative time in seconds multiplied by 1000, ie, an ***activity output*** of 10000 corresponds to a cumulative processing time of 10 s. The ***activity***, A, is defined as the ratio of the cumulative processing time to the sampling time, ie, the fraction of the sampling time the probe was active. The activity gives an overestimate of the effective dead time of the probe as those particles that arrive in the beam while the probe is processing a previous particle and are still within the beam when probe processing is completed will be registered. The manufacturer thus suggests the following correction be applied to measured counts, N_c, to obtain the actual counts, N_a.

$$N_a = N_c / (1 - kA) \qquad \text{(B2)}$$

where k is an empirical correction factor, to account for the amount that the activity overestimates the actual dead time. The manufacturer suggests a value of 0.7 for k. Other investigators,

however, have reported k values between 0.5 and 0.7 (Baumgardner 1983, Cerni 1983, Baumgardner et al 1985). For Ontario Hydro's probe, a value of about 0.55 has been found generally to give good agreement with the alternate method discussed below.

The second correction method was suggested by Baumgardner et al (1985) and relies on knowledge of probe characteristics. They derive the following expression

$$N_c = N_a \frac{(T-\tau)}{T} \exp(-\lambda\tau_1) \qquad \text{(B3)}$$

where T is the sampling duration, τ is the accumulated dead time during the sampling period, λ is the rate of arrival of particles in the beam that can cause coincidence events (essentially those particles passing through the DOF and a region of equal length on either side of the DOF), and τ_1 is the average particle transit time. Baumgardner et al (1985) derive the following approximate expression for these factors.

The cumulative dead time is

$$\tau = N_t(\tau_2 - \tau_1) \qquad \text{(B4)}$$

where N_t is total strobes and τ_2 is the slow delay or reset time of the probe (10.5 µs in our case). Expression (B4) only holds when $\tau_1 > \tau_3$, where τ_3 is the probe fast delay time (2.5 µs in our case). Baumgardner et al (1985) also give an expression for $\tau_1 < \tau_3$, which is generally only appropriate for very fast sampling velocities such as those characteristic of aircraft mounting.

The average particle transit time is

$$\tau_1 = 0.78\ W/v \qquad \text{(B5)}$$

where W is the beam width (0.227 mm in our case) and v is the sampling flow velocity. For example, at v = 30 m s^{-1}, τ_1 = 7.6 µs.

The particle arrival rate is

$$\lambda = 3\ N_a\ W\ v\ L_D \qquad \text{(B6)}$$

where L_D is the depth-of-field.

Because λ depends on N_a, (B4) must be solved by iteration. The program FSSP.WK1 outputs the 9th and 10th iteration to check for convergence.